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Publication date:
2015

Citation for pulished version (APA):

Boyd, B., Straatman, B., Mangalagiu, D., Rasmussen, S., & Rathje, P. (2015). The Carbon City Index (CCI): A Consumption Based, Regional Input-Output Analysis of Carbon Emissions. SANTA FE INSTITUTE. (SFI Working Paper, Vol. 2015-12-049).

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SFI WORKING PAPER: 2015-12-049

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The Carbon City Index (CCI): A consumption based, regional input- output analysis of carbon emissions

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Abstract

This paper presents a consumption-based Carbon City Index for CO₂ emissions in a city. The index is derived from regional consumption and not from regional production. It includes imports and exports of emissions, factual emission developments, green investments as well as low carbon city development policies and stakeholder engagement. The index is based on a multi-region input-output model used in most parts of the world for more than half a century. We demonstrate the index through comparative case studies of three Danish regions: a rural region with a city center, the municipality of Sønderborg, a mid-sized city region, the municipality of Odense, and a metropolitan area, the municipality of Copenhagen. We demonstrate how city initiatives implemented to reduce emissions are translated into easy to access input-output parameters changes and how the index transparently assesses the emission impact of various possible municipal climate plans over time. As such, the index promotes the export of solutions from one region on another, as it enables policy makers to look elsewhere for best practices and test them on their own city before potential implementation. The index facilitates an easy to use and transparent comparison of factual and planned emission policies in different cities and can inform regional sustainability discussion and contribute to the dissemination of solutions.

Keywords: Carbon Baseline, Carbon Footprint, Greenhouse Gas Emissions, Import and Export of CO₂, Carbon City Index, Input-Output Analysis, Stakeholder Engagement

1 Introduction

More than half of the world's rapidly growing population today lives in cities. Highly populated cities are naturally intensive areas of activity, which mobilize resources, goods, services, financial, and human capital. According to UN-Habitat [2012; 2006], there are three important trends in the urbanization processes. First, the biggest cities will be found mainly in the developing world: "Mega cities" (more than 20 million people), are gaining ground in Asia, Latin America and Africa. Second, more than half of the world's urban population lives in cities of fewer than 500,000 inhabitants, and almost one-fifth lives in cities of between 1 and 5 million inhabitants. Third, cities of the developing world will absorb 95% of urban growth in the next two decades, and by 2030, will be home to almost 4 billion people.

Most studies agree that cities are responsible for about 80% of all anthropogenic GHG emissions [Hoornweg, 2011, Satterthwaite, 2008]. Cities are realizing the urgency to confront the climate challenge, the need to be based on a sustainable economy and to steer away from a development path linked directly to increasing GHG. However, many roadblocks slow down the exchange of promising ideas and innovations among cities, which are looking to improve their sustainability [Hoornweg, 2011, Satterthwaite, 2008].

In terms of defining sustainable urban development, we adopt the definition proposed by Camagni [1998]: "a process of synergetic integration and co-evolution among the great subsystems making up a city (economic, social, physical and environmental),

which guarantees the local population a non-decreasing level of wellbeing in the long term, without compromising the possibilities of development of surrounding areas and contributing by this towards reducing the harmful effects of development on the biosphere”.

The aim of this paper is to present a transparent and easy to use Carbon City Index (CCI) including low carbon city development policies and global impacts of the city through imports and exports. Since international agreements on carbon emission reductions are exceedingly difficult to negotiate, and since more progress is being made at the regional scale, this Index could become an easy to use standard for benchmarking, comparing, and importantly, exporting sustainability solutions from one region to another. The paper is structured as follows: Section 2 presents an overview of existing initiatives to enhance urban sustainability, section 3 introduces the methodology and section 4 presents the application of the Index to three Danish cities, Sønderborg, Odense and Copenhagen. In section 5 we present how the Index can evaluate different low carbon city policies. We conclude the paper with a discussion of the advantages and limits of the developed Carbon City Index.

2 Sustainable Cities Initiatives

2.1 Measuring city sustainability

Cities around the world implement sustainability initiatives aiming at lowering their GHG emissions and combating climate change.

Urban sustainability indicators are very important when setting targets, evaluating performance and facilitating dialogue between policy makers, experts and the society [Verbruggen and Kuik, 1991]. But measuring and accounting at city level are difficult. The measuring is mostly done at national level and focuses on the evaluation of the environmental performance associated with domestic production. Current methods for estimating GHG, such as the reference approach and sectorial approach, adopted by the IPCC, estimate the amount of anthropogenic emissions generated within the political boundaries of countries. This principle is referred to as territorial or producer responsibility [Wiedmann et al., 2007, Turner et al., 2007].

However, this accounting scheme encourages developed countries to artificially reduce their domestic emissions and shift their environmental burden through globalization and international trade, while simultaneously increasing global emissions through freight transportation and exporting heavy industry to developing countries, and importing raw materials and energy intensive products [Schütz et al., 2004, Browne et al., 2008]. Thus, globalization has allowed for 'pollution haven', i.e. relocation of traditional labor-intensive industries such as textiles and heavy manufacturing industries to developing countries with

less stringent environmental regulations [Akbostanci et al., 2007]. Therefore, the assessment of the environmental performance of the national economy requires distinguishing between emissions from domestic production within a nation's boundaries versus imported goods produced elsewhere to satisfy domestic demand. The same goes for exported goods [Ravetz, 2000].

Carbon footprint is defined as “a measure of the total amount of CO₂ emissions that are directly and indirectly caused by an activity or is accumulated over the life stages of a product”.[Wiedmann and Minx, 2007, page 4]. The same authors provide a comprehensive review of the assessment of environmental impacts embodied in trade and their appropriateness to estimate the footprints of production, consumption and trade, with the possibility to track their origin via inter-industry linkages, international supply chains and multi-national trade flows.

Measuring cities' sustainability and GHG emissions poses several challenges. First, the spatial unit of a city. Second, there is a gap between developed and developing countries. Some sustainability indexes and indicators tend to over- or underestimate developed countries as compared with developing countries. For example, the Environmental sustainability index (ESI) and the Environmental Policy Index (EPI) favor developed countries due to their economic status and environmental pollution control supported by their high income [Esty et al., 2008]. Moreover, available data are scarcer in developing countries. Third, defining sustainability indicators based on information and data collected at different spatial and temporal scales [Putzhuber and Hasenauer, 2010].

Although indicators are being used increasingly to assess performance of city

sustainability in many initiatives, there is no assessment system universally accepted. Tanguay et al. [2010] surveyed 23 studies of the use of urban sustainable development indicators in developed western countries. In total, 72% of the indicators apply to only one or two studies, and very few indicators are found in more than five studies. Shen et al. [2011] proposed -- based on the various sets of indicators promoted by international and regional organizations, such as UN Habitat, World Bank, European Commission -- a list named International Urban Sustainability Indicators List including 115 indicators grouped into 37 categories and structured along four dimensions aiming to examine the variations between individual practices. Renn [1995] developed a regional concept of qualitative growth and sustainability and articulated a regional conversion strategy at the level of the Baden-Württemberg region in Germany, while Browne et al. [2012] applied a number of biophysical sustainability metrics to an Irish city-region in order to evaluate the effect of methodological pluralism when measuring urban sustainability. Putzhuber and Hasenauer [2010] argue that indexes and indicators focus on specific contexts and features more than needed because core requirements for city sustainability have not been clearly defined.

At a more global level, the Global Footprint Network (GFN) accounts for demand and supply of the biosphere's regenerative capacity in their national ecological footprint accounts methodology and framework [Kitzes et al., 2008, Borucke et al., 2013], while Haberl et al. [2007] quantify and map the human appropriation of net primary production in earth's terrestrial ecosystems.

2.2 Comparable approaches

The C40 Large Cities Climate Leadership Group¹ comprises some of the world largest cities that share sustainability experiences and technologies. Its action plan involves not only direct CO₂ reductions but also protection methods for climate crises. The Clinton Climate Initiative (TCCI)² launched in 2006 serves as the exclusive implementing partner of the C40 Group. The Project 2° is a non-profit network of cities, which started as collaboration between TCCI, Microsoft and ICLEI - Local Governments for Sustainability.

The Low Carbon Cities Program (LCCP)³ in UK, funded by DEFRA and delivered by Carbon Trust and Energy Saving Trust supports UK cities in developing citywide carbon reduction strategies. The carbon calculator is based on input data (stationary emission sources, transport, waste and water) and the output includes CO₂ emissions on consumption data.

The Siemens Green Cities Indexes are projects assessing and comparing cities leading in sustainability in different regions of the world. The Index scores cities on energy and CO₂, land use and buildings, transport, waste, water, sanitation, air quality, and environmental governance based on 30 indicators. Sixteen are quantitative and measure how cities currently perform, while the remaining 14 qualitative indicators assess policies and plans – e.g., city's commitment to reducing the environmental impact of energy consumption. The regional indices are adapted to accommodate region-specific variations

¹ <http://www.c40cities.org/>

² <http://www.clintonfoundation.org/our-work/clinton-climate-initiative>

³ <http://www.lowcarboncities.co.uk/cms/>

in data quality and availability and environmental challenges.

Several studies express skepticism regarding the influence indicator development has on real change in policy and sustainability performance. Some argue this is caused by an over-emphasis on quantitative assessment at the expense of qualitative measurement [Gahin et al., 2003], the inadequate selection of indicators guiding city sustainability [Briassoulis, 2001], and the lack of consensus on urban sustainability indicators [Legrand et al., 2007].

A common issue of all mentioned initiatives is the limited availability of local data on GHG emissions. Therefore, only direct emissions are calculated or estimated by sector. The sectors and subsectors usually considered are: industrial and commercial (electricity use, gas use, oil and solid fuel use, waste, agricultural processes and fuel use, off road machinery), domestic (electricity use, gas use, oil and solid fuel use, home and garden machinery transport (road transport, railways), land use, land use change, and forestry.

As shown above, the methods used for calculating urban emissions vary significantly across cities and none accounts for imports and exports. We propose in the following section such an index, the CCI.

3 The CCI: presentation and methodology

The City Carbon Index (CCI) project started in Sønderborg, a municipality in southern Denmark working towards carbon neutrality by 2029 [ProjectZero, 2011]. The CCI measures the CO₂ balance in cities, which is (i) consumption based, (ii) includes emissions embedded in trade, (iii) measures the investment in clean technology, (iv) reflects impact of stakeholder engagement in policy initiatives as well as (v) is able to assess potential impact of climate plans developed in a city on another one.

An index calculating city's actual (production and consumption-based) carbon footprint including the carbon footprint embedded in trade must take into account economic activity, import, export, local final demand, local industrial landscape and the ability to change these elements, both in the city and elsewhere. Input-output analysis provides these elements in a structured format linking economic activity, consumption, GHG emissions and policy.

There are two main frameworks for input-output analyses. One, originally developed by Leontief [Leontief, 1986, Peters and Hertwich, 2004], focuses on transactions between industries. The second fits data collection methods by statistical agencies and focuses on commodities [Madsen and Jensen-Butler, 1999]. Depending on what data is most readily available both methods can be used with CCI. In this paper, we use the second framework consisting of Make-Use matrices fitting readily available data in Denmark.

3.1 Multi-region input-output modeling at the municipal level

In the present analysis we consider three regions: the region r , which will often be a municipality, the region roc – rest of the country, and the region row – rest of the world.

Let M^r be the $n \times m$ matrix ($n, m \in N$) of regional production that specifies each of the n industries make which of the m commodities. Total output per industry is gr and total output in terms of products is qr , which are obtained by summing the rows and columns of M^r respectively. M^{roc} and M^{row} are defined similarly, but then for their regions. They also have associated total production expressed in commodities q^{roc} and q^{row} (see Table1).

TABLE 1

Secondly, let Z^{rr} , Z^{rroc} and Z^{row} be $n \times m$ matrices that define trade of commodities within region r and between the three regions r , roc and row , while Z^{ocr} , and Z^{rowr} are $n \times m$ matrices that define the trade between roc and row . Next, let U^r , U^{roc} and U^{row} be the $n \times m$ matrices that specify per industry the use of regional, rest of country (roc), and rest of world (row) commodities respectively. s^r , s^{roc} and s^{row} denote the total use (consumption) of commodities originating from the region, the rest of the country, or the rest of the world respectively. In addition to intermediate use of commodities, there is also final demand for commodities, denoted by the variables y^r , y^{roc} and y^{row} .

The Center for Regional and Tourism Research (CRT) has developed a model for regional input-output data at a municipal level, providing above data for 98 municipalities x 117 sectors x 164 commodities. The data are in fixed 2005 prices and latest final data is currently from 2008. From this data set we derive the necessary components for an emission analysis.

3.2 Economic activity coupled with CO₂ emissions

Fuel use for the production of commodities has to be considered to make the link between economic activity and CO₂ emissions. We are interested in determining the yearly regional emissions $RE(t)$, the imported- and the exported emissions $IE(t)$ and $EE(t)$, so that we can calculate the net emissions $NE(t)$, where t refers to the year.

The emission factor for an industry is defined as the emissions in tonnes of CO₂ per million of DKK gross output. Based on private communication with Olsen [2012], we have constructed appropriate emission factors by combining fuel use per industry FU , (dimensions 117 by 31), the CO₂ emission rates (tonnes of CO₂) associated with the industry's fuel use R (dimensions 117 by 31), and the gross output in DKK for each of the industries at a national level G (vector for 117 industries) as follows. The data needed for the calculation of the emission factors is available for the years 1996 to 2008, so that trends in emission factors over the decade are incorporated into the analysis.

The yearly emissions $E(t)$ per industry per fuel are calculated by

$$E(t) = FU(t) \times R(t) \quad (1)$$

where each element of $FU(t)$ is multiplied by the corresponding element of $R(t)$.

This results in a 117×31 matrix $E(t)$.

When the row totals are calculated for each of the 117 industries the total emissions per industry are known. Thus when divided by the gross output $G(t)$ per industry the emission factors $F(t)$ are obtained as

$$F(t) = E(t) \cdot \{1, \dots, 1\}' / G(t) \quad (2)$$

Using equation (23) from the Appendix⁴ to express regional gross output, it

⁴ For details on the somewhat convoluted matrix algebra, please see Appendix.

follows that regional emissions RE in year t are given by

$$RE(t) = g^r(t) \cdot F(t) = \quad (3)$$

$$[(A_i^r(t)g^r(t) + D^r(t)(y^r(t) + Z^{rroc}(t) + Z^{rrow}(t))] \cdot F$$

Imported emissions IE for year t can be expressed as the emissions from imported intermediate consumption (roc and row) plus the emissions from final demand imported from elsewhere (roc and row)

$$IE(t) = [(A_i^{rroc}(t) + A_i^{rrow}(t))g^r(t) + D^{rroc}(t)y^{rroc}(t) + D^{rrow}(t)y^{rrow}(t)] \cdot F(t) \quad (4)$$

Exported emissions EE for year t is determined by the total production in the region minus what is used in the region (intermediate consumption by industry and used by final demand)

$$EE(t) = (g^r(t) - A_i^r(t) g^r(t) - D^r(t) y^r(t)) F(t) \quad (5)$$

Net emissions NE for year t are subsequently defined as the sum of regional emissions and imported emissions minus the exported emissions of year t

$$NE(t) = RE(t) + IE(t) - EE(t) \quad (6)$$

3.3 The policy translator

The CCI also include the effects of investment and policy support based on (1)

Collection of investments and initiatives impacting GHG emissions. (2)

Translating this list into data for the regional input-output analysis.

Table 2 illustrates this process using [Riddlestone and Plowman, 2009] report on London's sustainability. Initiatives are classified in eight categories. The second column specifies the action taken. These first two columns show local initiatives to be accounted in CCI. However, to include such initiatives in the index, analysis is necessary to translate them into data used in the input-output analysis. First, which factors from the input-output analysis are impacted by the initiatives is determined (column 3).

TABLE 2

Next, the user specifies which industries are affected and goals set (in percentages of change) used afterwards to generate regional projections for future technological coefficients, final demand and emission factors. These projections are translated – via economic impact assessment – into future regional emission projections.

The CCI takes energy consumption into account, as well as consumption of other goods and services, regardless if they are produced locally or elsewhere. This implies that in our analysis we can include a comprehensive list of initiatives. Every initiative that reduces or changes consumption (final demand), or every policy that changes the production process by replacing an input by another, affects the regions footprint.

4 Application of the Carbon City Index to Danish municipalities

In this section we apply the methodology and tools developed in the previous section to three Danish municipalities (“Kommunes”), Sønderborg (BKM540, 1996: 75,000 citizens, 2007: 77,000 citizens), Odense (BKM461, 1996: 184,000 citizens, 2007: 187,000 citizens), Copenhagen (BKM101, 1996: 484,000 citizens, 2007: 510,000 citizens) as well as the whole country (BKM1alt, 1996: 5,275,000 citizens, 2007: 5,476,000 citizens). These municipalities are selected so to represent a small city, a mid-size city (the third largest) as well as the largest city in the country.

At a national level Denmark annually releases the National Inventory Report, based on local authorities’ data on emissions of CO₂ and other GHG, such as CH₄ (Methane), N₂O (Nitrous Oxide), HFCs (Hydro fluorocarbons), PFCs (Perfluorocarbons) and SF₆ (Sulphur hexafluoride). CO₂, as the most important GHG, contributed with 81.7 % of Denmark’s total emissions in 2006. The emissions are aggregated into seven main sectors: Energy 61.5%, Transport 19.3%, Agriculture 13.6%, Industrial Processes 3.5%, Waste 1.9%, Solvent and Other Product Use 0.2% and the rest on land use, land use change, and forestry.

4.1 Case study Sønderborg

Sønderborg municipality (77,000 inhabitants) is located in southern Denmark near the German border. It covers approx. 500 km² and main activities are business, industry,

farming and higher education.

Calculating a carbon baseline for Sønderborg is part of the ProjectZero⁵ that seeks to coordinate sustainability in the Sønderborg region. ProjectZero has the declared vision of creating a CO₂-neutral Sønderborg region by 2029 based on sustainable growth and with many new green jobs as a result. This vision is being implemented by a public-private partnership involving the municipality and mayor businesses in the area. Through these partnerships and by sharing solutions, ProjectZero aims to establish a leading position for Denmark in CO₂-neutral growth and sustainable cities.

ProjectZero's CO₂ baseline for the Sønderborg area was calculated on the basis of a "production perspective", meaning that emissions are calculated as originating from where they are actually generated. Production data is gathered from the area's energy suppliers, multiplied by specific emissions factors and aggregated to form the CO₂ baseline. The baseline calculations show a total CO₂ emission for all sectors of 674.022 tons. This yields 8.76 tons/capita⁶.

The goal of Sønderborg is CO₂-neutrality by 2029 and the milestone of a 25% reduction of CO₂-emissions in 2015. To reach these goals a Masterplan and a Roadmap have been elaborated based on initiatives such as expanding existing district heating networks and converting supply to CO₂-neutral sources including cogeneration (CHP),

⁵<http://www.projectzero.dk/>

⁶ A new release of Danish national datasets has led to small adjustments in Sønderborg's baseline calculations. For the sake of consistency we kept the earlier published figures so that each municipal analysis is based on the same national datasets.

geothermal energy, thermal solar heating, absorption heat pumps and biomass boilers; converting oil and natural gas furnaces in rural areas to heat pumps; converting part of the transportation demand to bio-ethanol and electricity [SRC International, 2009b,a]:

- Expand existing district heating networks and convert supply to CO₂-neutral sources including cogeneration (CHP), geothermal energy, thermal solar heating, absorption heat pumps and biomass boilers
- Convert oil and natural gas furnaces in rural areas to heat pumps
- Establish biogas plants supplying district heating, industrial processes and transportation
- Convert part of the transportation demand to electricity
- Convert part of the transportation demand to bio-ethanol
- Expand existing on-shore wind turbine capacity and establish new capacity
- Establish central and decentralized photo voltaic facilities
- Employ substantial energy efficiency measures throughout the project
- Introduce a dynamic energy system – a Smart Grid

Several initiatives are well underway. Also, a host of citizen and industry involvement programs, such as the ZEROhousing and ZEROcompany programs respectively, have been initiated and proven successful in securing noteworthy energy savings in both segments.

4.1.1 Regional emissions for Sønderborg, emissions in trade and net emissions

The municipal data available through the Center for Regional and Tourism Research (CRT) provides an overview of total economic activity for 1996 to 2007. The database contains economic data for each of the 117 industries, but as these data are confidential only aggregated economic activity is presented here. Figure 1 provides an overview of regional production, imports and exports of the region. The figure displays a steady economic growth from 1996 to 2007 and import and export are well balanced when compared by their values.

FIGURE 1

The disaggregated economic activity underlying the totals displayed in Figure 1 can be translated into emission figures by applying emission factors (see equation 2) for each of the industries. For each of the years 1996 to 2007 the regional, imported, exported, and net emissions are determined as outlined in Equations 3, 4, 5, and 6.

Figure 2 shows the emissions of economic activity of Sønderborg associated to the regional production, to import and to export. Note that although import and export are well balanced in terms of their value over the years 1996 to 2007, in terms of CO₂ emissions import is responsible for considerably higher emissions than export.

FIGURE 2

As exported goods and services are destined for somewhere else, their associated

emissions are also accounted for somewhere else and the exported emissions are graphed negatively. Due to the higher carbon content of imports the net emission for Sønderborg are considerable higher than the regional emissions. For the origin of regional emissions refer to Figure 3.

FIGURE 3

4.1.2 Projections

As detailed above, Sønderborg has implemented a range of initiatives to reduce emissions in their climate plans [SRC International, 2009a]. These initiatives have been translated into model parameter changes in order to assess the cumulative effects. Sønderborg uses the year 2007 as their baseline and all targets set in the climate plan [SRC International, 2009a] are relative to this base year. Furthermore the various targets are to be reached in the years 2012, 2015, 2021 and 2029. Overall, the municipality aims at carbon neutrality of their energy system in 2029.

In order to make projections we have applied the SRC International [2009a] targets to final demand, emission factors and coefficients. In other words, when an initiative targets an increased efficiency of space heating by 25% in 2012 and 35% in the year 2029, then final demand for the industry “350030 Steam and hot water supply” is reduced accordingly. Starting at 0% reduction for the base year 2007 we interpolate in between target years up to the year 2030. The same idea applies to initiatives that target a percentual

reduction of emission factors of certain industries, as well as to initiatives that aim to shift corporate procurement of inputs away from carbon intense ones to lower carbon inputs. The latter is an example of a change in technical coefficients.

FIGURE 4

The combined effect of changes to final demand, emission factors and coefficients is graphed in Figure 4. Emissions embedded in import are reduced slightly as a result of reduced final demand; however, the emission factors behind the industries of imported goods and services are not impacted by local initiatives. Exported emissions on the other hand are reduced significantly, partly as a result of reduced coefficients, partly as a result of reduced emission factors applied to local production. There is no reduced export because of reduced final demand, as local initiatives do not impact final demand outside the region. Regional emissions are reduced significantly because of a combination of all three impacts: reduced final demand, reduced coefficients, and reduced emission factors. Although regional emissions show a significant potential reduction, net emissions remain relatively high as import is now almost fully responsible for the net regional emissions. This in particular illustrates one of the strengths of the CCI method. It tells the actual emissions stemming from human activity within the given area. It is not ignoring goods and services produced elsewhere, and the index is not “rewarding” outsourcing of carbon intense production. As a matter of fact, outsourcing might make things worse, as one gives away the control over the emission factors associated with the production.

Figure 5 provides an overview of the impact on net emissions as defined in

equation 6 of three different types of initiatives that affect the coefficients, the final demand, or the emission factors. Shifting procurement by industries has an effect, though small. Shifting final demand, either through changing consumer choices or through efficiency measures that result in reduced demand for space heating or electricity reduces the net emissions considerably. When all three types of initiatives are combined, the cumulative effects are significant. However, as was shown in Figure 4, most of the remaining net emissions are associated to import of goods and services.

FIGURE 5

Despite the planned initiatives, based on Sønderborg's published numbers and plans, it is not clear how Sønderborg can become carbon neutral by 2029 mainly because of imported emissions. However, the regional emissions will likely drop dramatically to below 3 tonnes/capita.

4.2 Case study Odense

The city of Odense with 192,000 inhabitants aimed at 8% CO₂-reduction in 2012, 50% CO₂-reduction in 2025, and CO₂ neutrality in 2050. In its climate plan [Odense Kommune, 2011] the following initiatives to reduce regional CO₂ emissions are enlisted:

- Improved district heating with renewable energy resources: wind, water, biogas, biomass, solar, earth, geothermal
- Improved municipal (as an organization) performance in efficient electricity use and space heating
- Corporate engagement to reduce electricity use and improve space heating
- Citizens initiatives to reduce electricity use and improve space heating
- Transport: more cycling, collective traffic, upgrading of the public transit system.

4.2.1 Odense's economic activity and associated emissions

The municipality of Odense also features a strong export sector. The analysis of Odense includes all the economic activity including shipping. Figure 6 shows trends in economic activity over the 11 years preceding 2007, the base year in their climate plan. Figure 7 displays the associated emissions.

Figure 8 shows that indeed much (85% in 2007) of the regional emissions are due to the provision of electricity and space heating. (Odense's climate plan [Odense Kommune, 2011] states 58% of the emissions are caused by electricity and heat

consumption.) As in other municipalities, addressing energy related emissions is crucial.

FIGURE 6

FIGURE 7

4.2.2 Emission projections

As mentioned above the municipality of Odense focuses on reduced energy consumption within its own organization, as well as on reduced energy use by its citizens and companies. Initiatives address emissions and efficiency of space heating and electricity, both at the supply side and the demand side. By 2025 the following reductions are targeted: emission factors of the production and distribution of electricity and the provision of steam and hot water for space heating by 54% and 8% respectively; final demand by 12% and 34% respectively; Companies' electricity, gas, steam and air conditioning use by 20%; transportation sector by 35%. This package of initiatives leads to the results in Figure 9.

In its climate plan, Odense targets a variety of actors: municipality as an organization to reduce electricity and space heating use, citizens to curtail their energy consumption and demand of carbon intensive goods and services, companies to reduce their dependence on energy. These initiatives change the intermediate consumption of carbon intense products and effectively change the technological coefficients in the input output analysis. Furthermore, the climate plan addresses the emission factors of energy producers. As a result, Figure 10 shows that each type of local actors can make a difference in the total regionally emitted CO₂.

FIGURE 8

FIGURE 9

FIGURE 10

Based on the published plans, Odense's regional emissions in 2025 are projected to be around 10 tonnes CO₂/capita with net emissions around close to 7.5 tonnes/capita.

4.3 Case study Copenhagen

The municipality of Copenhagen, with 555,601 inhabitants in 2012 (urban area 1,213,822 and metropolitan area 1,935,746) plans to reduce their annual CO₂ emissions by 20 percent between 2005 and 2015, which equates to an annual reduction of 500,000 tonnes of CO₂. Copenhagen envisions itself as the first carbon neutral capital worldwide by 2025. To reach the 20 % reduction goal in 2015 Copenhagen has developed a climate plan (CCP) with 45 initiatives that address six different areas [City of Copenhagen, 2009]:

- Energy: convert from fossil fuels to renewables and use energy more efficiently to result in a reduction of 375000 tonnes of CO₂ per year (7 initiatives).
- Transportation: the area where the initiatives do the most for the health of citizens to result in a reduction of 50000 tonnes of CO₂ per year (15 initiatives)
- Buildings: energy efficient renovation and management as good investment for well-being, climate and finances to result in a reduction of 50000 tonnes of CO₂ per year (10 initiatives)
- Copenhageners: focus on all daily life issues in households, work places, schools, institutions and the municipality itself through information, consultation and training to result in a reduction of 20000 tonnes of CO₂ per year (9 initiatives)

- Urban development: a common approach across all sectors and in close collaboration with local initiatives to result in a reduction of 5000 tonnes of CO₂ per year (4 initiatives)

To achieve the CO₂ target, bike bridges and new bike paths are being built so to encourage Copenhageners to choose bikes over cars [Danish Energy Agency, 2011].

4.3.1 Copenhagen's economic activity and associated emissions

Figure 11 shows the importance of export for Copenhagen region. The impact of exported goods and services becomes even clearer in the context of associated CO₂ emissions.

Figure 12 shows that almost all regional CO₂ emissions are exported, and thus that the net emission are only marginally higher than the imported emissions.

FIGURE 11

FIGURE 12

The shipping industry is responsible for significant emissions associated to exported goods..In 2007 over 90% of the regional emissions were associated to the transportation industry. Although Copenhagen's municipality harbors the company headquarters responsible for these emissions, most of the transportation services are exported and as such the associated emissions are not tallied to the Copenhagen account. In our analysis of municipal CO₂ reduction initiatives international shipping emissions obscure what is truly happening within the municipal borders. Therefore in the case of Copenhagen we have chosen to exclude the shipping business from our analysis. See Figure 13 for the adapted history of per capita emissions. This adaptation is optional as it merely improves the readability of the graphs. It does not significantly impact the net regional emissions, as almost all of the shipping services are provided to the customers outside the municipality. Figure 14 displays the origin of the Copenhagen municipality CO₂ emissions excluding international shipping.

FIGUER 13

4.3.2 An analysis of Copenhagen's climate plan

The initiatives of the CCP for which potential CO₂ reduction is quantified are translated into changes to final demand, coefficients and emission factors for the economic and environmental impact assessment (as detailed in Section 3), Figures 15 and 16 are obtained. Figure 15 shows that with a successful implementation of the CCP, Copenhagen can reduce their regional emissions by about 29% from 2005 to 2015. Currently some

plans are available for the period 2015-2025, but little detailed information has been published.

FIGURE 14

Based on our analysis of available plans, a further reduction of 9% in regional CO₂ emissions after 2015 to a total reduction of 38% in 2025 compared to 2005. However, the 2005 figure resulting from our analysis of Copenhagen's economic activity (minus the shipping industry) is higher (approximately 3,500,000 tonnes versus 2,500,000 tonnes).

Although it seems that Copenhagen is well underway to achieve the planned reductions for 2015, it is at the moment unclear how the carbon neutrality in regional production will be achieved in 2025. When detailed climate plans for 2015-2025 are released, further analysis will have to be needed to establish further potential reductions. Figure 16 shows that current initiatives will reduce regional emissions to approximately 4.5 tonnes of CO₂ per capita (based on a fixed population of 555,601 municipal inhabitants - 2012 figure).

FIGURE 15

However, as in Sønderborg, when embedded emissions are included in the analysis the picture changes somewhat. Slightly over 5.5 tonnes of CO₂ per capita are embedded in import of goods and services, while slightly over 1.5 tonnes of CO₂ per capita of the regional production is due to exported goods and services. This results in a net per capita emission of approximately 8.5 tonnes of CO₂.

Figure 16 shows that most of Copenhagen's reductions result from energy related emissions. Only 5% of annual reductions are supposed to be obtained from citizens' behavioral changes.

FIGURE 16

4.4 Denmark at country-level

By following a similar method as applied above to determine municipal emissions associated to local production, import and export, we can determine these emissions for Denmark as a whole. In this case there is no domestic trade and all import and export is foreign and we apply the same method. Data for this analysis is publicly available⁷. By combining data on import, export, and gross output for each of the 117 industries in the DB07 classification, population numbers and figures on economic activity we generate total emissions and emissions per capita. When all industries are incorporated in the

⁷ <http://www.statbank.dk/statbank5a/default.asp?w=1024>

analysis the per capita CO₂ domestic emissions are considerably higher than expected (18.7 tonnes per capita in 2007). Much of these emissions are related to export, and this is confirmed by the much lower net emissions of 10.1 tonnes per capita (2007). Once more a large part of these emissions stem from the shipping industry. When the shipping industry is excluded from the analysis we obtain Figure 17. The national per capita figures (9.4 tonnes per capita in 2007) are coherent with the official figures (9.1 tonnes per capita in 2007 [United Nations Statistics Division, 2012]).

FIGURE 17

5 Comparison and benchmarking

5.1 Export of CO₂ reduction solutions

Besides the ability to assess a municipal climate plan's potential impact on GHG reductions, the presented index also allows to experiment with other climate plans. As such the index can promote the export of solutions, as it enables policy makers to look elsewhere for best practices. This is illustrated in Figures 18 (a) and (b). Figure 19 (a) shows the past, current and projected emissions of Sønderborg when it implements the municipal climate plan. Figure 18 (b) shows past, current and projected emissions of Sønderborg in the case it would implement the climate plan developed for London [Riddlestone and Plowman, 2009].

FIGURE 18 (a) and (b).

By comparing the two figures it becomes clear that London's climate plan leads to potential local GHG emission reductions faster than what is currently envisioned in Sønderborg and the per capita emissions in 2050 would be lower. Projected local 2050 emissions in Sønderborg are 2.29 tonnes per capita versus 1.85 tonnes per capita with the Sønderborg and the London climate plans respectively. Projected 2050 net emissions for

Sønderborg under these two climate plans are 5.73 versus 5.33 respectively. This shows that although Sønderborg is making good progress in reducing emissions and can still look for inspiration elsewhere.

5.2 Comparative benchmarking

Competitive benchmarking as widely used tool in marketing management, can be defined as a technique for assessing relative marketplace performance of an organization. The value of this technique can be used to inform about the relative standing of organizations [Hollensen, 2010, Johnson et al., 2010]. There are different approaches to benchmarking such as historical, industry or best-in-class benchmarking, but also cities can be benchmarked with each other. City benchmarking provides a comparison of main elements that can help with implementing future strategies, as well as for evaluating differences [Luque-Martinez and Munoz-Leiva, 2005].

City managers requests for tools and resources, which improve community participation and promote better practices on land and resource use [Snyder, 2001]. Benchmarking consists of identifying, learning and implementing the most effective practices and capacities from one city in order to improve actions of other cities [Luque-Martinez and Munoz-Leiva, 2005]. The CCI will provide dimensions for comparing the examined cities.

TABLE 3

TABLE 4

The benchmarking profile in Table 3 shows the dimensions where cities are strong, average or weak when evaluating the effects and the numbers obtained by studying five dimensions for each city. The ranking in Table 4 is based on the figures in the benchmarking profile (Table 3). The municipalities in Table 4 are scored according to their performance and initiatives where 5 is the best and 1 the worst score. This qualitative ranking benchmarking aims at simplifying and comparing the municipalities, which is illustrated in Figures 19 and 20.

FIGURE 19

FIGURE 20

Clearly Sønderborg has the best CCI scores using both benchmarking methods and the scores vary a bit depending on which Low Carbon Plan is implemented: its own or the London plan. Odense scores better than Copenhagen, while Odense and Sønderborg have similar current CO₂ emission profiles. Again it should be noted that the Copenhagen Municipality (~510,000 citizens, 2007) does not correspond to the larger Copenhagen metropolitan area (~1,146,000 citizens, 2007) and therefore probably scores a better CCI than it would, had we used data for the full metropolitan area.

6 Discussion and alternative approaches

The approach we developed is in essence based on linear extrapolations of modeled regional input-out data sets and we used input-output data at a very fine spatial scale. Two caveats need to be noted here though:

First, the data used at the municipal level is modeled data and not raw data. Although this is to some extent also the case for national input-output data, the effort required to “generate” municipal data is considerable. For details on how this was achieved see Madsen and Jensen-Butler [1999], and note here that the used data depends on the assumptions made by Madsen and Jensen-Butler.

Second, the application of Leontief inverse matrices to assess current and future economic and environmental impact of changes in economic flows depends on the assumption that technical coefficients do not change over time. Some of the coefficients were manipulated as a result of changing corporate procurement, but most remained untouched, implying that technological innovation is absent. For the scope of the analysis presented here this was considered sufficient, but one can argue that a highly dynamic system needs to be addressed accordingly. For options regarding the coevolution of technology, production and markets please refer to Straatman [2008] and Straatman et al. [2008].

For many cities, necessary data for the method presented above is not available at

the appropriate level of detail. In such cases one alternative is to use the RAS matrix adjustment method. The RAS procedure, whose name comes from the two vectors (r and s) and a matrix (A) used in the process, adjusts the technical coefficient matrix of a comparable region (or of the same region at different time) to the regional output, intermediate sales and intermediate consumption numbers. By means of this simple procedure it is possible to turn national input output accounts into regional ones, while taking into account the regional consumption and sales balances. The RAS method has much lower data requirements than the multi region input output analysis detailed above. RAS generates an approximation of the regional input output table [Sergento, 2009].

The RAS approach can dramatically expand the applicability of the presented method to include the many regions where the data, for multi-region input output analysis at municipal level, may not be readily available.

7 Conclusions

We have demonstrated that the City Carbon Index is a transparent and easy to use method to assess consumption based GHG emission and reduction policies for cities and regions. By analyzing past, current and planned economic activity and coupling these to associated emissions, the CCI provides a clear picture of past emissions and forward trends. By including emissions associated to import and export in the analysis, the emissions embedded in trade are also taken into account. Some municipalities are very export oriented and thus, with a consumer-based approach, a large part of the emissions are exported out of the region and will be on another region's account. All municipalities depend on import, and the CCI sends a strong message that cleaning up local industry only is not going to be enough. Therefore, claims of some municipalities becoming carbon neutral only based on local emissions are not warranted, as most of these municipalities incorporate emissions embedded in trade in their analysis. The proposed CCI approach also avoids the problem of double accounting.

Further, the CCI provides a clear overview of the impact of investments in clean technology. By reducing the emission factors of local industry, it is possible to significantly reduce the local emissions, and the projections provided by the CCI provide a clear illustration of the effects of such investments.

The CCI offers insight into the potential impacts of successful public and corporate engagement by allowing an analysis of the effects of changing final demand and changing technical coefficients. To some extent, investment in green technology is the easy part of

the solution. Although often significantly reducing emissions, implementing green technology locally is not going to be a complete solution. In order to become fully sustainable, and to be able to make the carbon neutrality claim, it will be necessary to shift both public consumption and corporate procurement culture such that low-carbon considerations are taken into account in every purchase decision made. These changes are of a different character than “simply” implementing clean technology. They require a different level of stakeholder engagement.

Finally, the CCI makes it easy to experiment with a wide variety of initiatives independent of which geographical area they have been developed in. Thus different municipalities can look for best practices anywhere and exchange ideas on how best to proceed with even remote regions. The CCI method, however, does require data on input and output at a local level, and for two reasons this can prove to be problematic: (1) often such data are not directly available and need to be collected where possible, and some data needs to be filled in by means of modeling. (2) Even if the local data is available most often the data are not publicly available and requires approvals for access. Despite these obstacles we argue here that the CCI is a simple, transparent, science based approach that enables cities to know where they are, to compare with other cities, to plan for the future, to make clear data-based policy decisions as well as seek and implement the best solutions developed elsewhere.

Using the CCI we have benchmarked three Danish municipalities Copenhagen (central part of the capital), Odense (a mid-size city) and Sønderborg (a smaller city) where the analysis clearly shows how the different cities rank compared to each other within the

five dimensions defining the CCI. Sønderborg and Odense have similar current per capita CO₂ emissions, which are lower than the per capita emissions in Copenhagen. Sønderborg clearly scores best on CO₂ emission improvements, corporate engagement, public policy engagement as well as per capita investments in clean technology. This is not surprising because of Sønderborg's recent history of significant engagement in low carbon initiatives. To investigate the impact of plans invented elsewhere, we also applied London's climate plan to Sønderborg. The calculated consequences show both advantages and disadvantages over Sønderborg's current climate plan.

Acknowledgements

We are grateful to the Region of Southern Denmark, the Initiative for Science, Society and Policy, the University of Southern Denmark, as well as the Danish National Science Foundation for partly financial support for the CCI project. We are also grateful to the staff at Statistics Denmark for making it possible to compile these studies. Further we are embedded to Kristian Lindgren and Luis Bettencourt and the many individuals at our respective institutions in particular at SDU and at SFI with whom we have discussed the potential and the limitations of the CCI concept.

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Table 1: Simplified structure of municipal Make-Use input output table

$I \backslash C$	Region	Rest of Country	Rest of World	Total
M A K E	$1 \dots m$ 1 $:$ n	$1 \dots m$ M^{roc}	$1 \dots m$ M^{row}	g^r
Total	q^r	q^{roc}	q^{row}	
T R A D E	$1 \dots m$ Z^{rr} $R \quad Z^{roc}$ Z^{rrow}	$1 \dots m$ Z^{rocr}	$1 \dots m$ Z^{rowr}	
U S E	$1 \dots m$ 1 $:$ $n \quad U^r$	$1 \dots m$ U^{roc}	$1 \dots m$ U^{row}	
Total	s^r	s^{roc}	s^{row}	
FD	y^r	y^{roc}	y^{row}	

Table 2: Examples of initiatives translated into information that can be analyzed by economic impact assessment (Riddlestone and Plowman, 2009)

Categories	Initiatives	Impact	Industries	2020	2025	2030	2050
Food	Emissions from farms	Coefficients					-40%
Consumer goods	Electronic goods	Final demand					-50%
	Longer lasting clothes	Final demand					-25%
Private services	Water consumption	Final demand					-41%
	Zero carbon heating	Emissions			-30%		
Built infrastructure	Local sourcing	Emissions		-2%			
	Improved efficiency	Coefficients		-20%			
	Diesel alternatives	Emissions		-7%			
Housing infrastructure	Reclaimed materials	Coefficients		-5.5%			
	Low-impact materials	Emissions		-10%			
	Durable materials	Coefficients		-2%			
Public services	Reuse of furniture	Coefficients					-2%
	Paper saving	Coefficients					-50%
Domestic energy	Behavioral change	Final demand					-6%
	Lightning/appliances	Final demand					-18%
	Renewable electricity	Coefficients					
Transport emissions	Aviation efficiencies	Coefficients					-10%
	Car clubs	Final demand					-50%

Table 3: Benchmarking profile

Dimensions:	Sønderborg	Copenhagen	Odense	Sønderborg+L
Urban CO ₂ profile	8.927	13.113	8.977	8.927
Trajectory	-0.131	-0.064	-0.097	-0.129
Corporate engagement	-0.012	-0.001	-0.009	-0.011
Public support	-0.051	-0.004	-0.020	-0.025
Clean technology	-0.068	-0.059	-0.068	-0.093

Table 4: Benchmarking ranking of the Carbon City Index

Dimensions:	Sønderborg	Copenhagen	Odense	Sønderborg+L
Urban CO ₂ profile	4	2	4	4
Trajectories	5	2	3	4
Corporate engagement	3	1	2	3
Public support	5	2	3	4
Clean technology	4	3	4	5

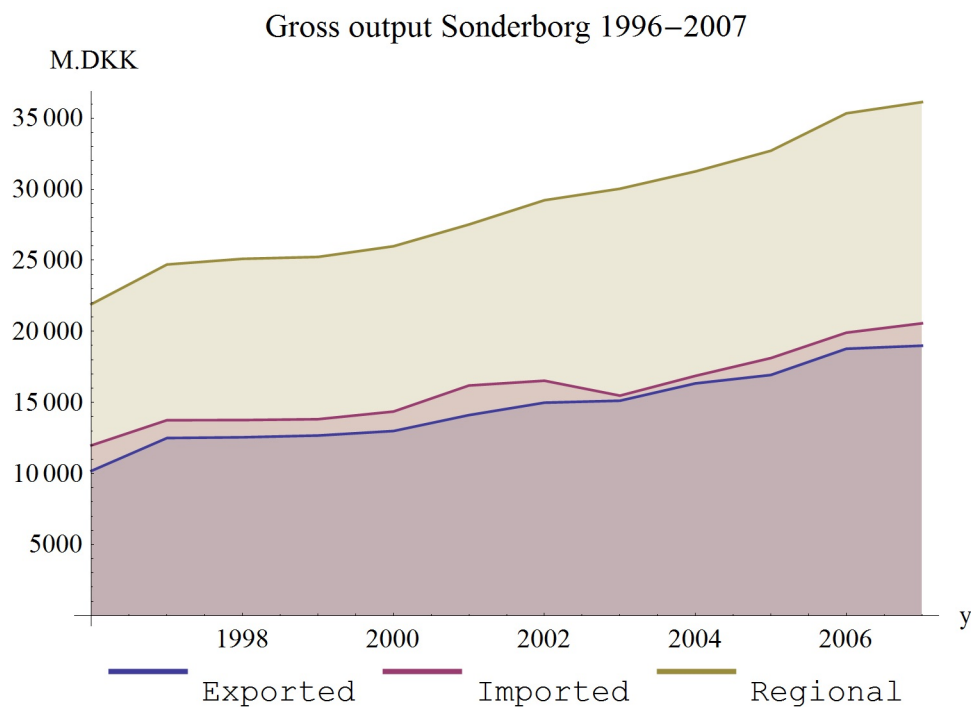


Figure 1: Economics of the Sønderborg region derived from the Center for Regional and Tourism Research (CRT) regional model. The figure graphs the value of regional production, import and export in million DKK in fixed 2005 prices.

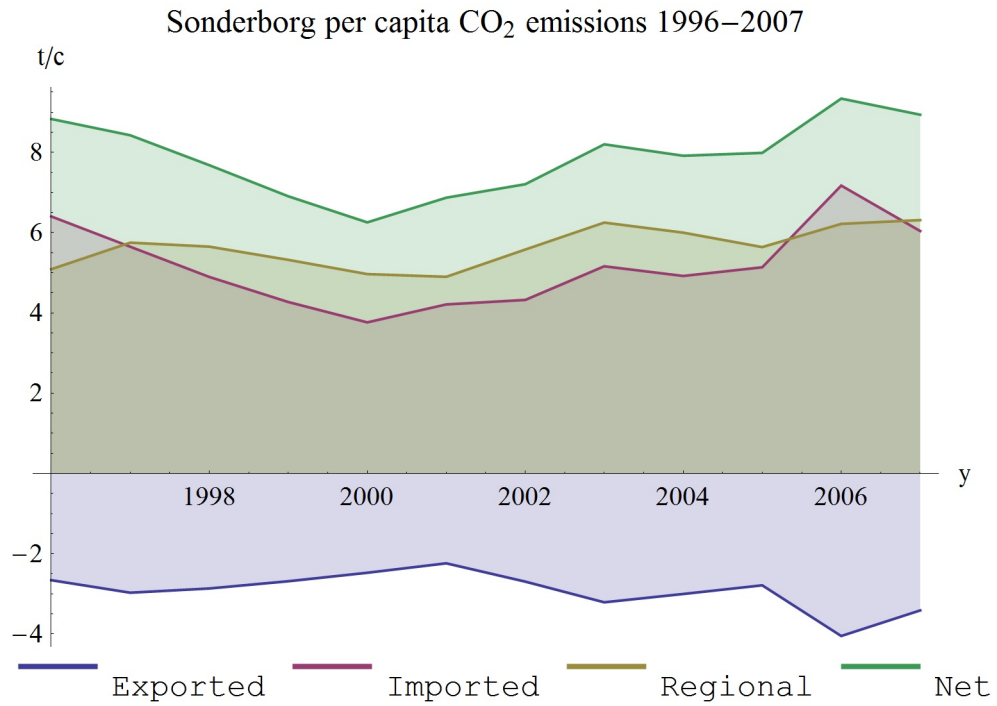


Figure 2: CO₂ emissions in tonnes per capita of the Sønderborg municipality when economic activity (local production, import and export) as derived from the CRT regional model is coupled to industry specific emission factors.

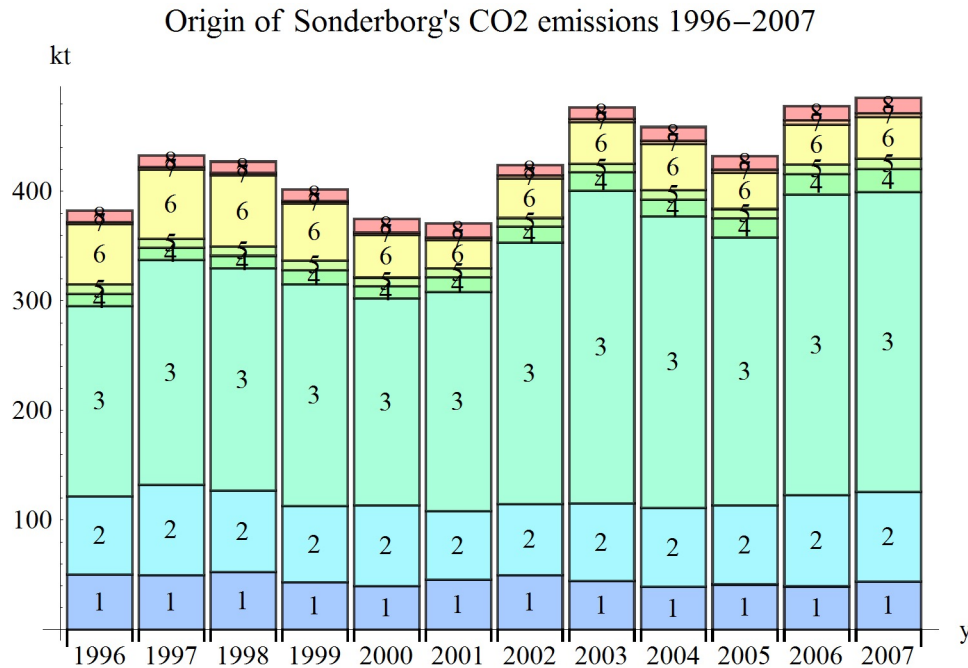


Figure 3: Regional CO₂ emissions in 1000 tonnes of the Sønderborg municipality when economic activity as derived from the CRT regional model is coupled to industry specific emission factors. The origin of emissions are specified for eight sectors: 1. Agriculture, fishing and quarrying, 2. Manufacturing, 3. Energy and water supply, 4. Construction, 5. Trade, hotels and restaurants, 6. Transport, post and telecommunications, 7. Finance and business, and 8. Public and personal services. The impact of a new cogeneration power plant (CHP) is reflected in the Sønderborg data (3 Energy and water supply) from year 1997.

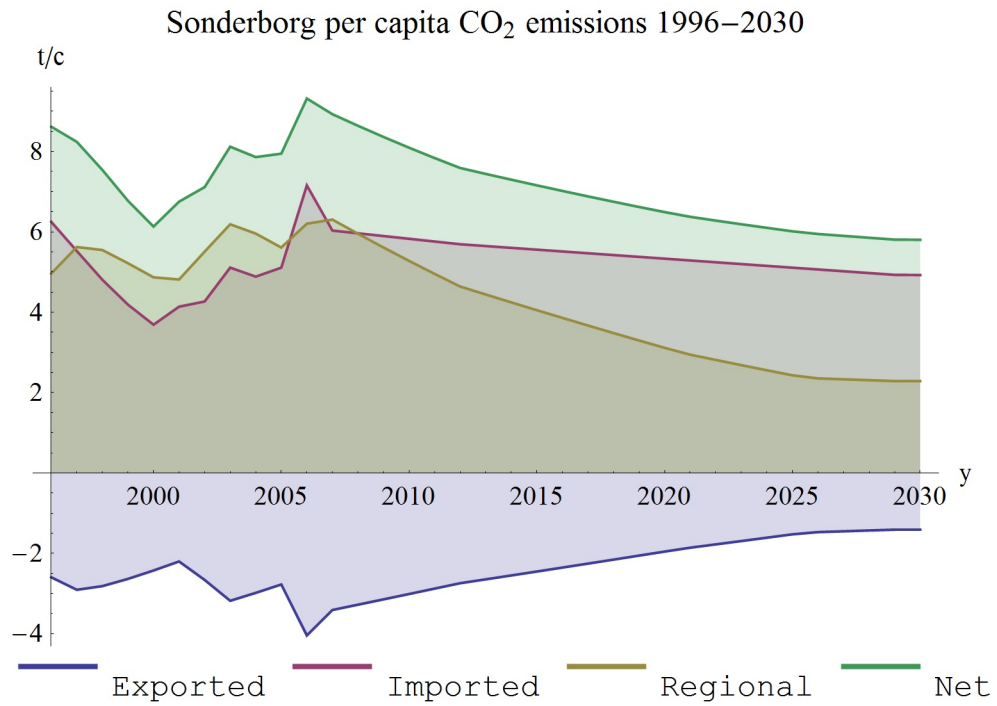


Figure 4: Overview of past and projected per capita emissions of the Sønderborg municipality as a result of the implementation of their climate plan.

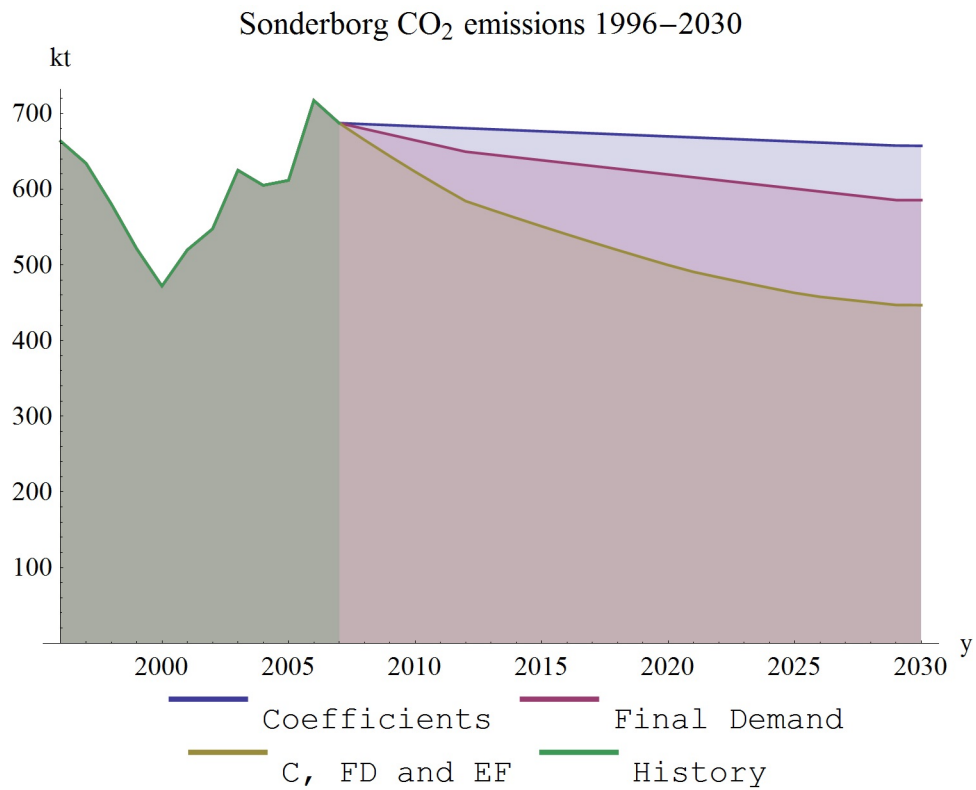


Figure 5: Comparison of the impact on net emissions of Sønderborg's initiatives affecting coefficients, final demand and emission factors.

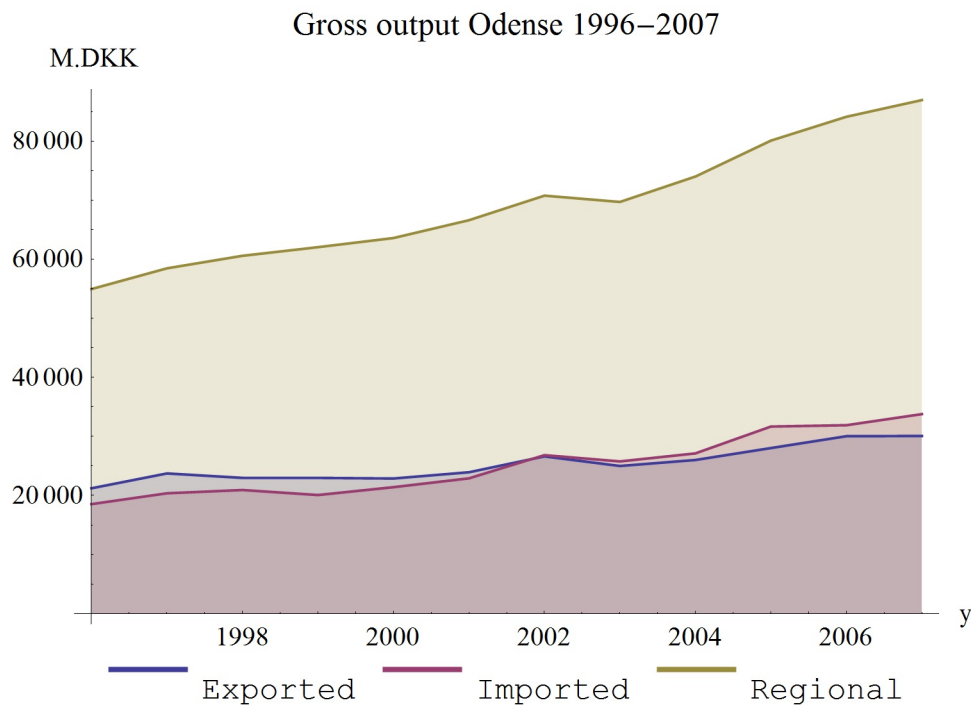


Figure 6: Economics of the Odense region derived from the CRT regional model.

The figure graphs the value of regional production, import and export in million DKK in fixed 2005 prices.

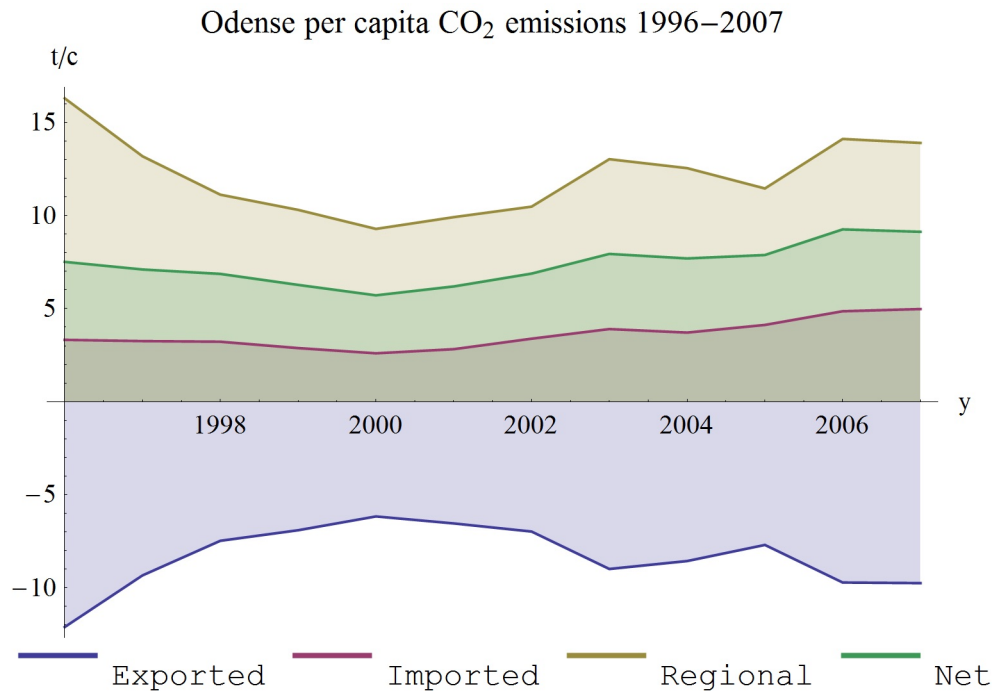


Figure 7: Associated per capita emissions of the Odense region derived from the CRT regional model. The figure graphs the CO₂ emissions of regional production, import and export in 1000 tonnes.

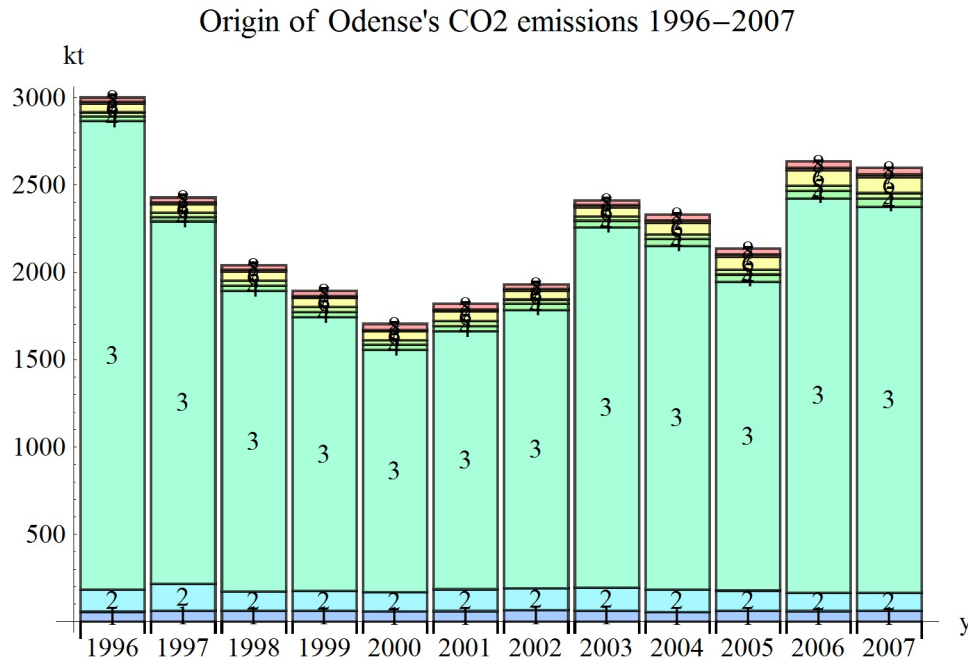


Figure 8: Regional CO₂ emissions in 1000 tonnes of the Odense municipality when economic activity as derived from the CRT regional model is coupled to industry specific emission factors. The origin of emissions are specified for eight sectors: 1. Agriculture, fishing and quarrying, 2. Manufacturing, 3. Energy and water supply, 4. Construction, 5. Trade, hotels and restaurants, 6. Transport, post and telecommunications, 7. Finance and business, and 8. Public and personal services. Odense municipality has a relatively large power generation capacity, which is both reflected in the relative size of 3 (Energy and water supply) and in the exported CO₂ emissions in Figure 9.

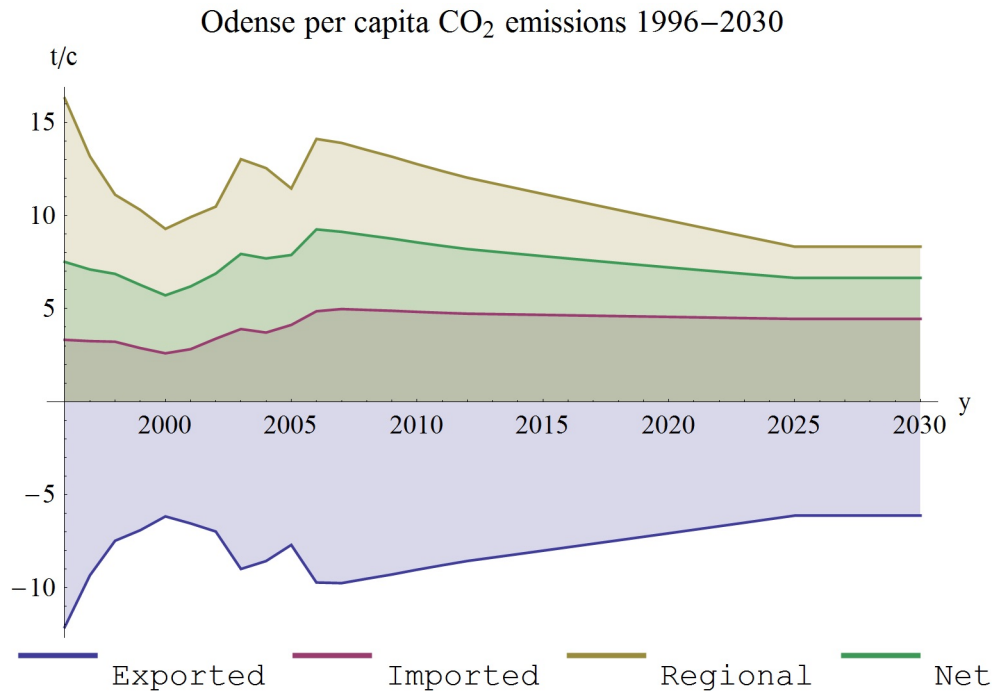


Figure 9: Overview of past and projected per capita emissions of the Odense municipality as a result of the implementation of their climate plan.

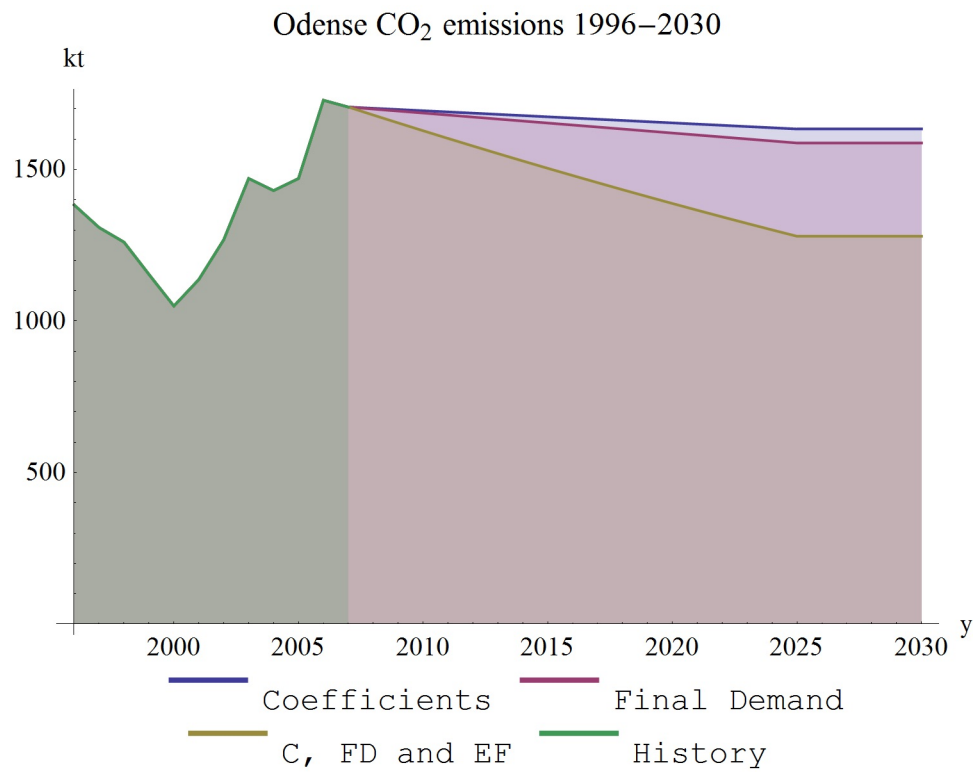


Figure 10: Comparison of the impact of Odense’s initiatives affecting coefficients, final demand and emission factors.

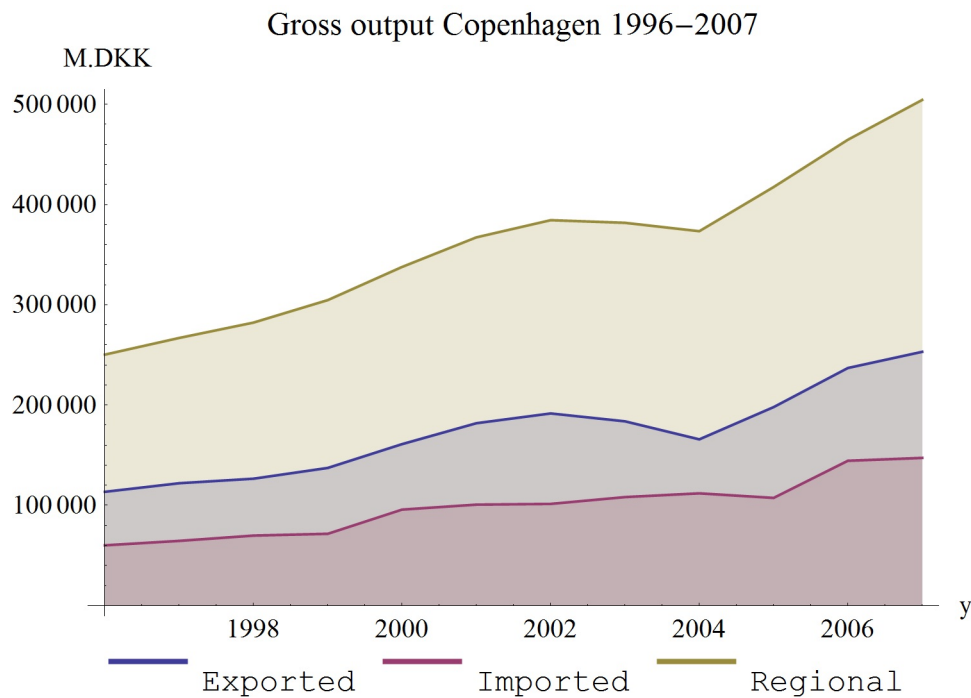


Figure 11: Economics of the Copenhagen region derived from the CRT regional model including the shipping industry. The figure graphs the value of regional production, import and export in million DKK in fixed 2005 prices.

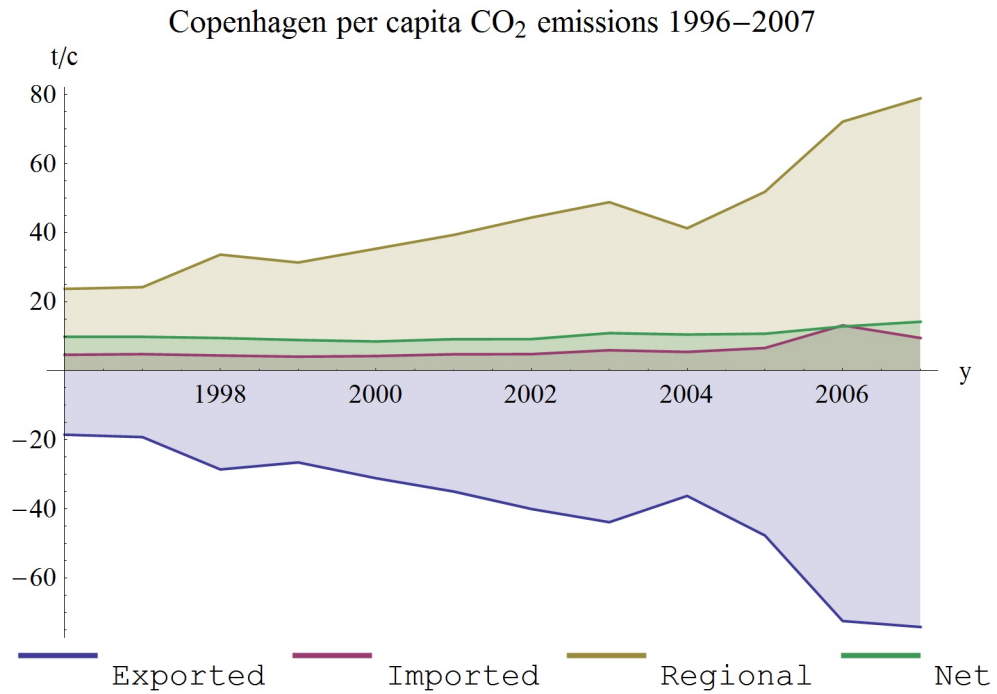


Figure 12: Associated emissions of the Copenhagen region including the shipping industry, derived from the CRT regional model. The figure graphs the per capita CO₂ emissions of regional production, import and export in tonnes.

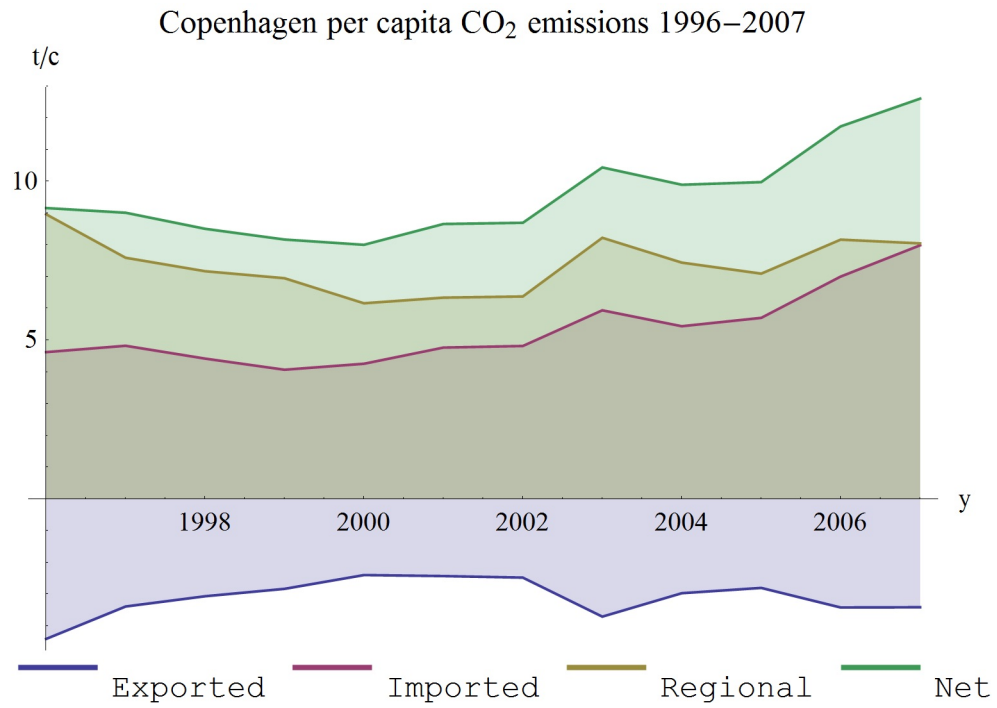


Figure 13: Per capita emissions (tonnes) of the Copenhagen municipality derived from the CRT regional model, but now excluding the shipping industry.

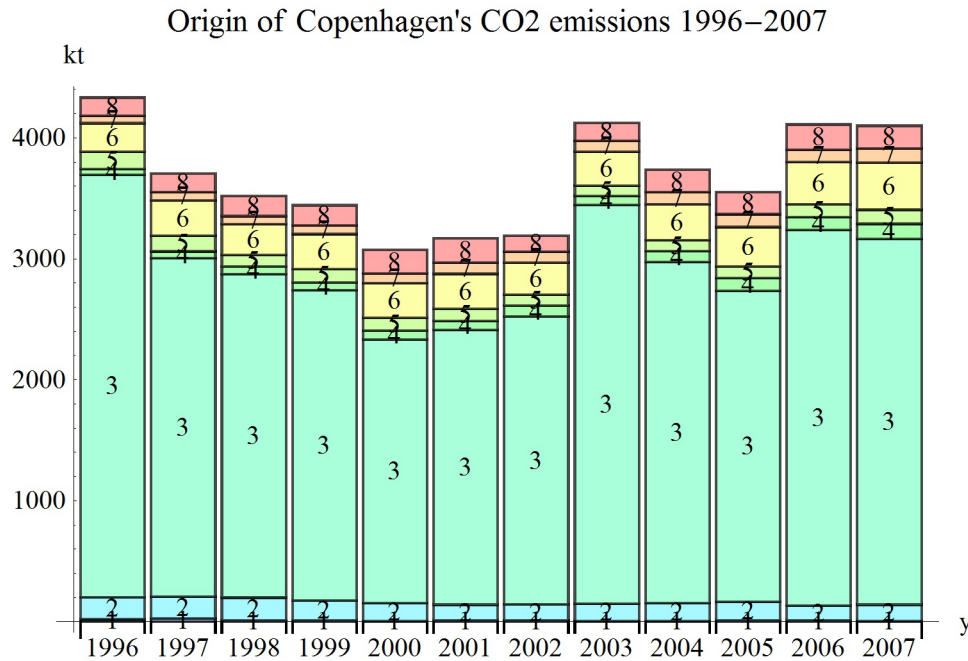


Figure 14: Regional CO₂ emissions in 1000 tonnes of the Copenhagen municipality (“Kommune”) when economic activity as derived from the CRT regional model is coupled to industry specific emission factors. The origins of emissions are specified for eight sectors: 1. Agriculture, fishing and quarrying, 2. Manufacturing, 3. Energy and water supply, 4. Construction, 5. Trade, hotels and restaurants, 6. Transport, post and telecommunications (without shipping), 7. Finance and business, and 8. Public and personal services.

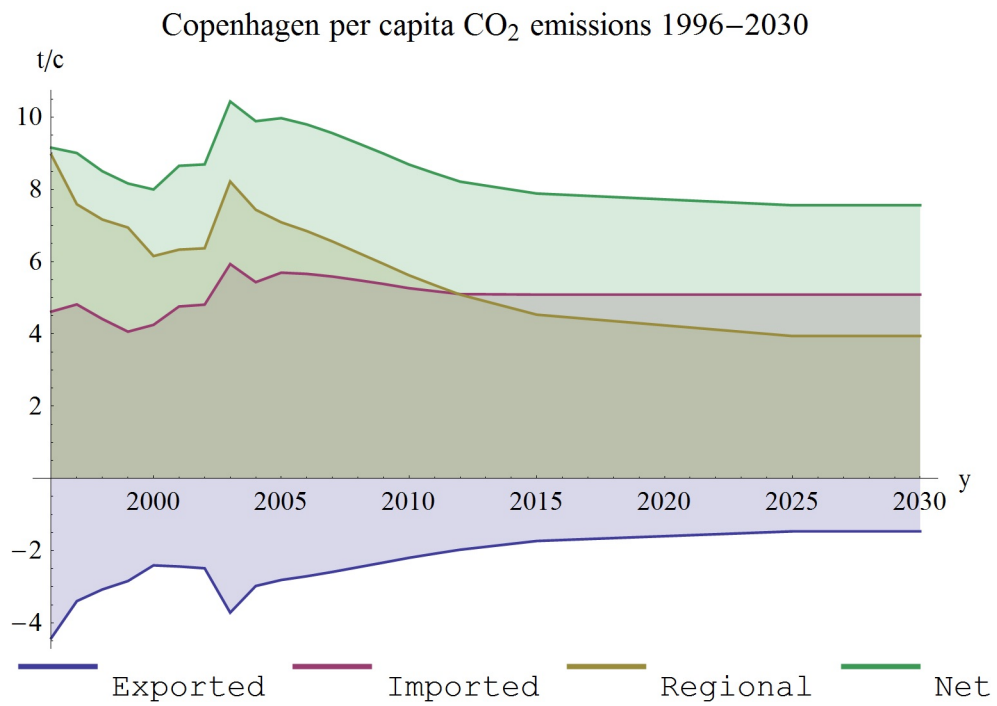


Figure 15: Overview of past and projected per capita emissions of the Copenhagen municipality as a result of the implementation of their climate plan.

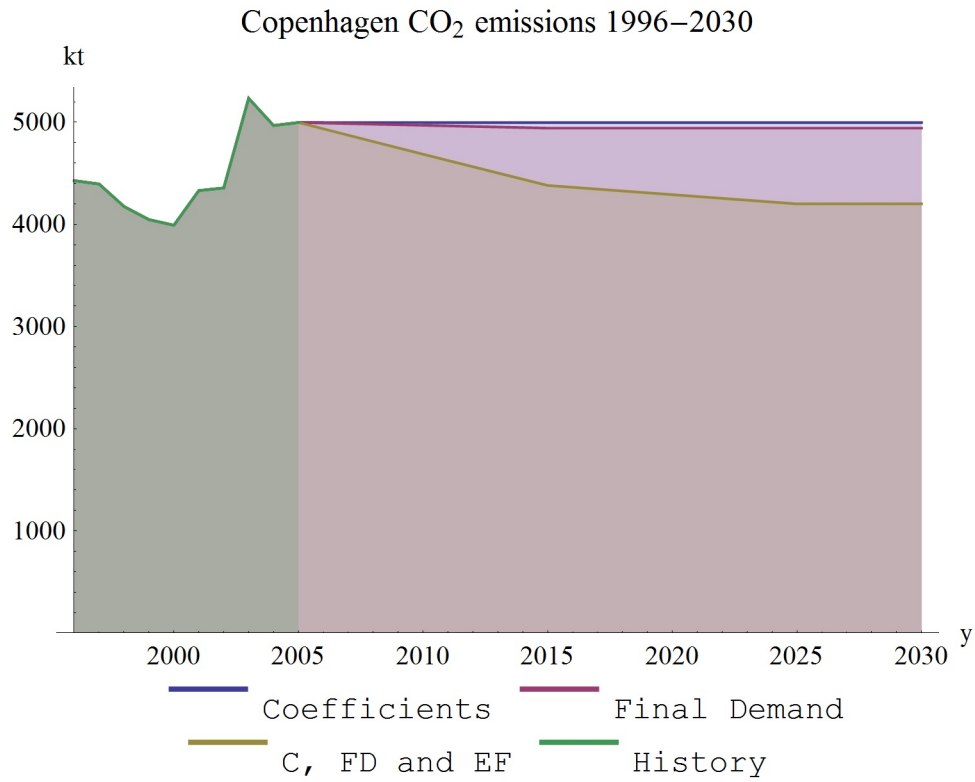


Figure 16: Comparison of the impact of Copenhagen’s initiatives affecting coefficients, final demand and emission factors.

Danish per capita CO₂ emissions 1996–2007

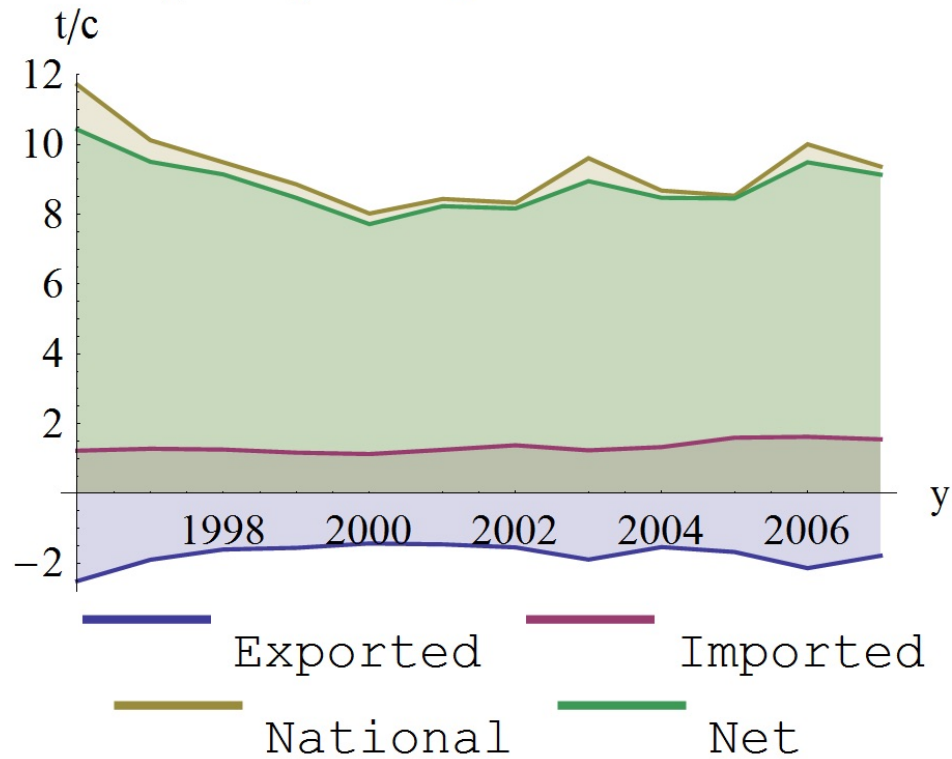


Figure 17: Trends in Danish per capita emissions (tonnes).

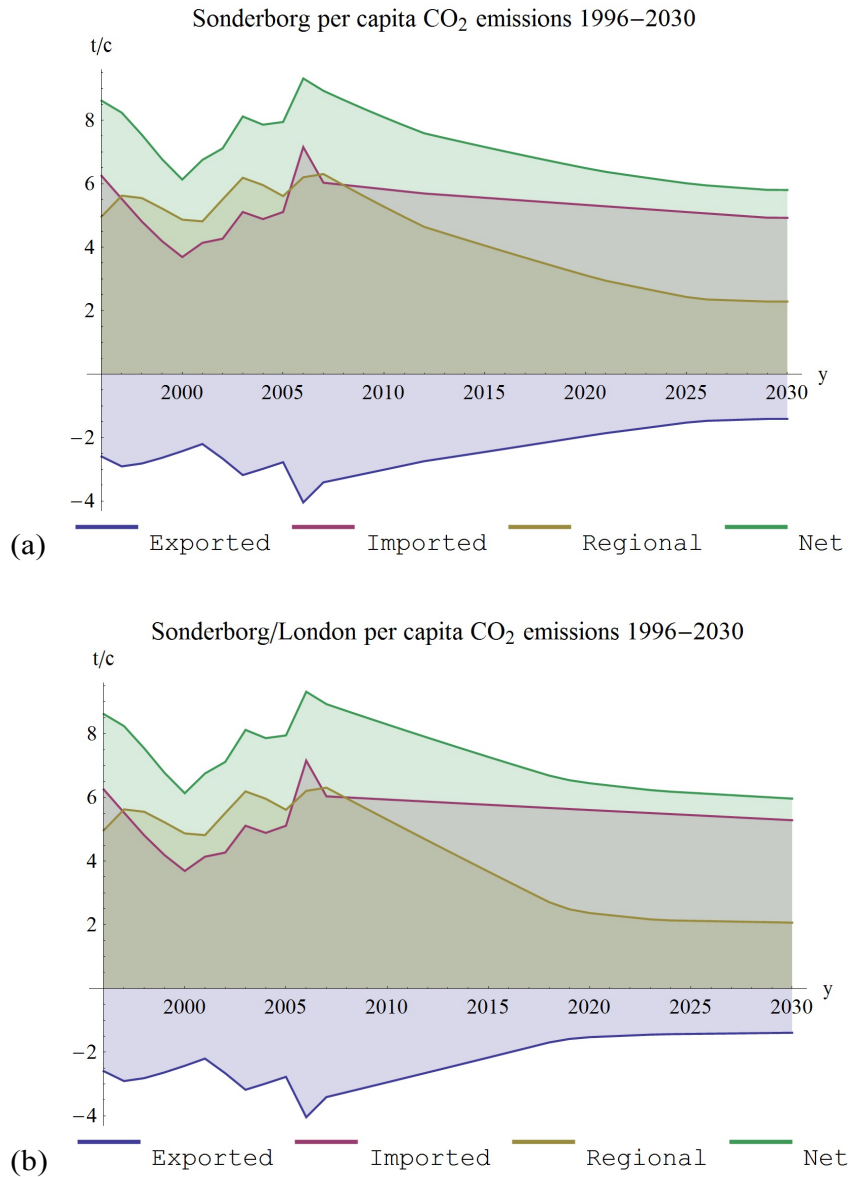


Figure 18: Overview of past and projected per capita emissions of the Sønderborg municipality as a result of: (a) the implementation of Sønderborg's Road map [SRC International, 2009a]; (b) a hypothetical implementation of *London's* climate plan [Riddlestone and Plowman, 2009]. Note the slightly more aggressive decrease in regional emissions with the London plan.

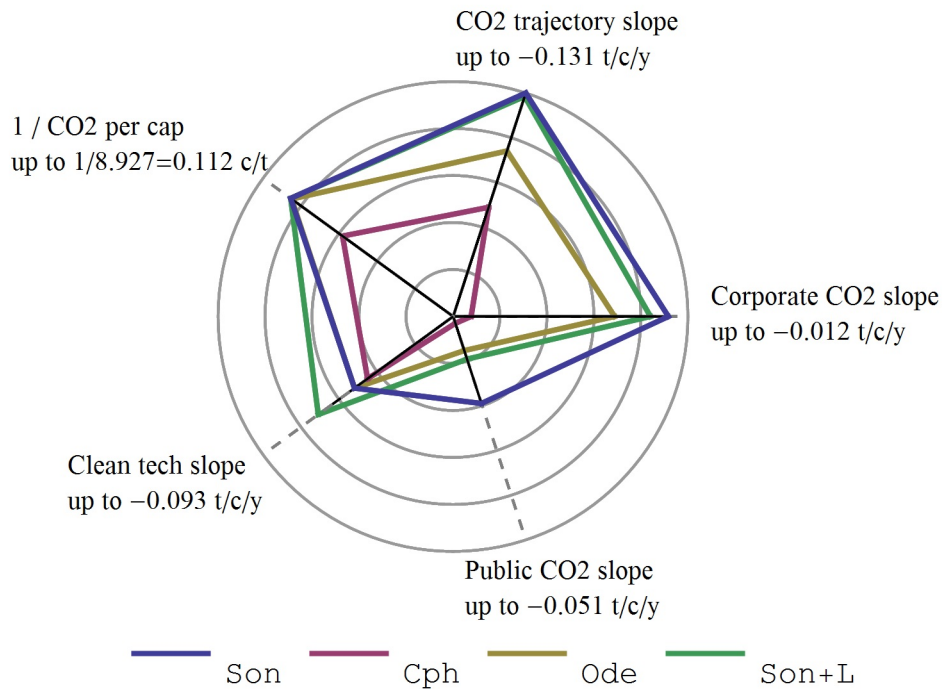


Figure 19: Benchmarking profiles for Sønderborg (current- and London's plan), Odense and Copenhagen. Benchmarking using the actual index numbers from Table 3 (and using the reciprocal value for CO2 per cap). Not surprisingly Sønderborg ranks best with a minor variations depending on the implemented climate plan, then Odense and Copenhagen. See text for detailed discussion.

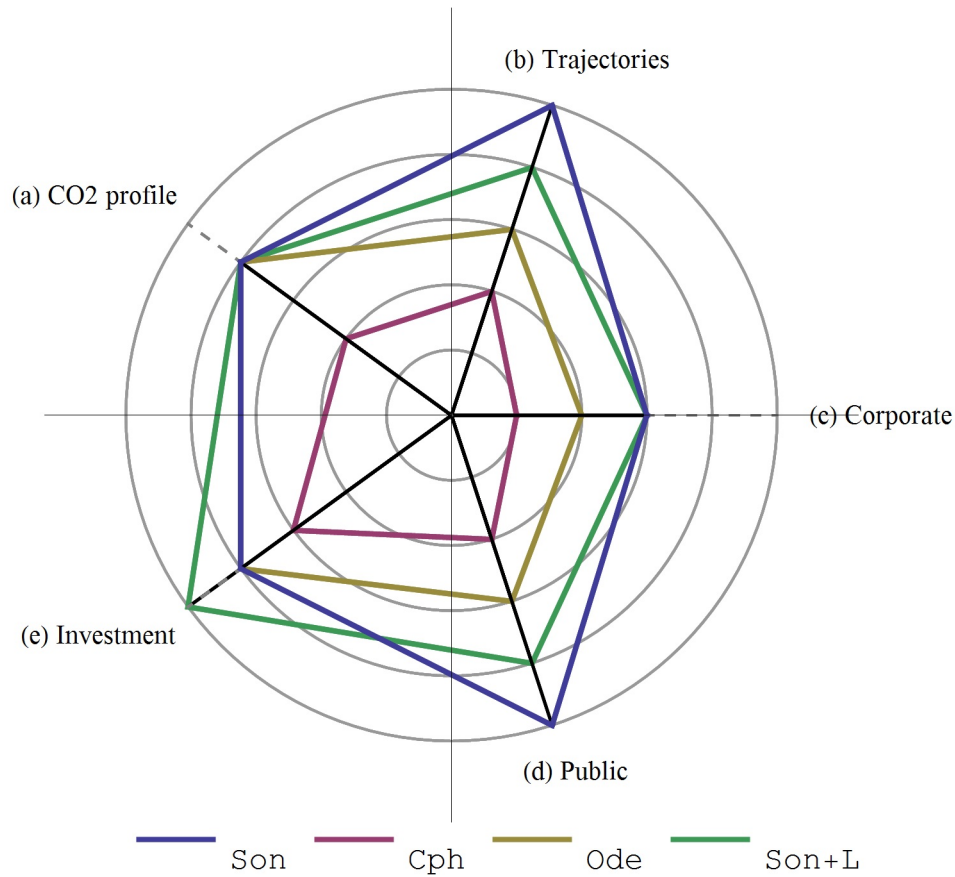


Figure 20: Benchmarking profiles for Sønderborg (current- and London's plan), Odense and Copenhagen. Benchmarking using the ranking numbers from Table 4 and thus scoring the four municipalities and their initiatives from 5 (best) to 1 (worst). First Sønderborg (current- and London's plans) then Odense and Copenhagen.

Appendix:

Multi-region input-output modeling details

Let M^r be the $n \times m$ matrix ($n, m \in \mathbb{N}$) of regional production that specifies each of the n industries make which of the m commodities. Total output per industry is g^r and total output in terms of products is q^r , which are obtained by summing the rows and columns of M^r respectively. M^{roc} and M^{row} are defined similarly, but then for their regions. They also have associated total production expressed in commodities q^{roc} and q^{row} .

Secondly, let Z^{rr}, Z^{rroc} and Z^{rrrow} be $n \times m$ matrices that define trade of commodities within region r and between the three regions r, roc and row , while Z^{rocr} , and Z^{rowr} are $n \times m$ matrices that define the trade between roc and row .

Next, let U^r, U^{roc} and U^{row} be the $n \times m$ matrices that specify per industry the use of regional, rest of country (roc), and rest of world (row) commodities respectively. s^r, s^{roc} and s^{row} denote the total use (consumption) of commodities originating from the region, the rest of the country, or the rest of the world

Table 5: Recall table 1: Simplified structure of municipal Make-Use input output table with n industries and m commodities. See text for details.

I\C		<i>Region</i>	<i>Rest of Country</i>	<i>Rest of World</i>	Total
M		$1 \dots m$	$1 \dots m$	$1 \dots m$	
A	1				
K	\vdots	M^r	M^{roc}	M^{row}	g^r
E	n				
Total		q^r	q^{roc}	q^{row}	
T		$1 \dots m$	$1 \dots m$	$1 \dots m$	
R					
A	R	Z^{rr}	Z^{rocr}	Z^{rowr}	
D	RoC	Z^{rroc}			
E	RoW	Z^{rrrow}			
U	1	$1 \dots m$	$1 \dots m$	$1 \dots m$	
S	\vdots	U^r	U^{roc}	U^{row}	
E	n				
Total		s^r	s^{roc}	s^{row}	
FD		y^r	y^{roc}	y^{row}	

respectively. In addition to intermediate use of commodities, there is also final demand for commodities, denoted by the variables y^r, y^{roc} and y^{row} .

The make matrix M^r for municipality r can be extracted from the data. The make matrix for the rest of the country M^{roc} equals national make matrix M^N minus M^r

$$M^{roc} = M^N - M^r. \quad (7)$$

M^{row} is assumed to be the same as M^{roc} as there is no data available for the rest of the world. $g^r, g^{roc}, g^{row}, q^r, q^{roc}$ and q^{row} are the row and column sums respectively of the three make matrices M^r, M^{roc} and M^{row} .

International trade Z^{rrrow} and Z^{rowr} (export and import to and from abroad respectively) is available. Domestic interregional trade Z^{rroc} and Z^{rocr} is equal to the sum of all outgoing and ingoing trade flows from r to the other municipal-

ities. Domestic intraregional trade Z^{rr} equals the regional gross output minus export

$$Z^{rr} = q^r - Z^{rr oc} - Z^{rr ow}. \quad (8)$$

For each municipality that we are interested in we can obtain the final demand fd in 164 commodities. What is not known, however, is where these commodities originate. In order to approximate y^{row} , y^{roc} and y^r we use Jensen [2007]’s “fixed product sales structure” assumption: *It is assumed that the relative shares in which a product is supplied from domestic production industries and import is the same no matter to which industry or final demand component it is delivered.*

$$y^r = \frac{Z^{rr}}{Z^{rr} + Z^{rr oc} + Z^{rr ow}} \cdot fd \quad (9)$$

$$y^{roc} = \frac{Z^{rr oc}}{Z^{rr} + Z^{rr oc} + Z^{rr ow}} \cdot fd \quad (10)$$

$$y^{row} = \frac{Z^{rr ow}}{Z^{rr} + Z^{rr oc} + Z^{rr ow}} \cdot fd. \quad (11)$$

The total intermediate consumption \bar{U}^r for region r can be extracted from the data. Let s be the column sums of \bar{U}^r . The trade coefficient matrices for r , roc and row can now be determined:

$$\hat{T}^r = \frac{Z^{rr} - y^r}{s} \quad (12)$$

$$\hat{T}^{roc} = \frac{Z^{rr oc} - y^{roc}}{s} \quad (13)$$

$$\hat{T}^{row} = \frac{Z^{rr ow} - y^{row}}{s} \quad (14)$$

where \hat{T} is the diagonal matrix with given fractions on the diagonal. The market share matrices D describes for each industry the market share they have in the

production of each of the commodities.

$$D^r = M^{r'} / q^r \quad (15)$$

$$D^{roc} = M^{roc'} / q^{roc} \quad (16)$$

$$D^{row} = M^{row'} / q^{row} \quad (17)$$

The use coefficient matrices describe the proportions of each commodity used by each industry. These matrices are calculated for r , roc and row by dividing the transpose of the use matrices by the total output per industry g^r :

$$\bar{B} = \bar{U}' / g^r \quad (18)$$

This allows the construction of industry-industry matrices for r , roc and row :

$$A_i^r = D^r T^r \bar{B} \quad (19)$$

$$A_i^{roc} = D^{roc} T^{roc} \bar{B} \quad (20)$$

$$A_i^{row} = D^{row} T^{row} \bar{B}, \quad (21)$$

and the total industry to industry matrix A_i is given by

$$A_i = A_i^r + A_i^{roc} + A_i^{row} \quad (22)$$

In terms of regional production per industry we can state the following:

$$\begin{aligned} g^r &= A_i^r \cdot g^r + D^r y^r + D^r (Z^{rrroc} + Z^{rrrow}) \Leftrightarrow \\ g^r &= (I - A_i^r)^{-1} D^r (y^r + Z^{rrroc} + Z^{rrrow}) \end{aligned} \quad (23)$$

The same Leontief inverse method [Leontief, 1986] applies to the total industry matrix A_i :

$$\begin{aligned} g^r &= (I - A_i)^{-1} \\ &\cdot (D^r (y^r + Z^{rrroc} + Z^{rrrow}) + D^{roc} (y^{roc} + Z^{rocr}) + D^{row} (y^{row} + Z^{rowr})) \end{aligned} \quad (24)$$

The above data and derivations are available for the years 1996 to 2008 in fixed 2005 prices for each of the 98 municipalities in Denmark.